COORDINATED MULTIFREQUENCY OBSERVATIONS OF THE BL LAC OBJECTS MRK 180, MRK 421, and MRK 501

S.L. Mufson, Indiana University; D.J. Hutter, Georgia State University; K.R. Hackney and R.L. Hackney, Western Kentucky University; Y. Kondo and C.M. Urry, NASA Goddard Space Flight Center; W.Z. Wisniewski, Lunar and Planetary Laboratory; M.F. Aller and H.D. Aller, University of Michigan

Over the past several years we have been investigating the properties of the three BL Lac objects Mrk 180, Mrk 421, and Mrk 501 using data gathered at ultraviolet, X-ray, optical, and radio wavelengths. These three objects are relatively nearby (z = .046, .031, and .034, respectively) composite systems in which a moderately luminous ($L = 10^{44}$ ergs/s) BL Lac object is found at the core of an elliptical galaxy (Ulrich 1978; Ulrich et al. 1975). These objects have been classified as BL Lacs because of the absence of emission lines in their spectra (Ulrich 1978; Ulrich et al. 1975), their linearly polarized optical continuum emission (Angel and Stockman 1980; Maza, Martin, and Angel 1978), and their flat radio spectra (Kojoian et al. 1976).

In order to understand the processes and conditions occurring within the nonthermal emission region of these BL Lac objects, we have obtained coordinated observations of them at ultraviolet, X-ray, optical, and radio wavelengths (Mufson et al. 1984a; Mufson et al. 1984b). These observations have given us a single epoch snapshot of the continuous spectrum of each object. The ultraviolet observations were obtained by the SWP and LWR cameras on IUE. The X-ray data were obtained by the IPC and the MPC on HEAO-2. The optical photometry consists of broadband BVRI measurements using the 1-m and 1.5-m telescopes of the University of Arizona Mt. Lemmon Observatory. The radio data were obtained with the University of Michigan computer controlled 26-m radio dish. The single epoch data for the three sources are shown in Figs. 1-3. These figures contain in addition archival radio and infrared data. The additional radio data demonstrate that the radio spectra of all the sources are flat.

For each time-frozen spectrum we have computed an inhomogeneous, relativistic jet model (Mufson et al. 1984a; 1984b). Our jet model is a modification of the jet described in Blanford and Königl (1979) and Königl (1981). Our main reason for choosing this model is the growing body of evidence suggesting that highly relativistic jet-like features are common in active galactic nuclei (Kellermann and Pauliny-Toth 1981). In the jets described here, relativistic electrons flow outward with bulk relativistic velocity along a free, conical jet. As they flow outward, the electrons emit synchrotron and self-Compton emission. In Figs. 1-3 we show our best model fits (χ^2/d.o.f. $\lesssim$ 1.5 for all cases) superposed on the data. It is evident that the model spectra fit the data well. It ought to be noted at this conference in particular the importance of the ultraviolet data to these calculations. The ultraviolet is the one spectral region where we are seeing synchrotron emission uncontaminated by galaxy emission, self-Compton emission, or optical depth effects.

A steepening synchrotron emission spectrum from the infrared to the ultraviolet, which is characteristic of relativistic jets (Königl 1981), is present in our model spectra. We can see from the figures that this spectrum, when extrapolated to high frequencies, can account for the X-ray observations. This implies that self-Compton emission is unimportant in these sources. In addition, the superposition of many different synchrotron spectra from different regions along the inhomogeneous jet produces the observed flat radio spectral index, nearly independent of the optical-uv spectral index. One further result of our computations is the relative contribution of galactic and nonthermal emission to the observed optical flux. Figs. 1-3 show that galaxy emission is most important for Mrk 501 and least important for Mrk 421.

We have found from our model fits that the physical structure of all three jets is very similar. The jets differ only in the angle at which they are aligned to the line-of-sight. We find that the relativistic particles all move outward with the same bulk velocity, a result which implies that all three jets have the same opening angle. In addition, the variation of the particle density and magnetic field strength with radius is similar for all three sources. Assuming that the particle density falls like r^{-n} and the field strength falls like r^{-m}, we find that $\langle n \rangle = 1.4$ and $\langle m \rangle = 1.3$, where the averages are taken over the values for the three model jets. For a jet which is free to expand adiabatically, conservation of particle number and magnetic flux predict that $n = 2$ and $m = 1.6$. Since the particle density in the models falls off more slowly than this prediction, particle injection must be occurring along the jet. The magnetic field strength, however, may be conserved along the jet.

Many of the differences observed in these three BL Lac objects can be ascribed to differences in the angle that the jets make with our line-of-sight. Our calculations show that the jet in Mrk 421 is most closely aligned with our line-of-sight ($\theta = 4.^{\circ}6$); the one in Mrk 501 is least closely aligned ($\theta = 23^{\circ}$). Since the jet in Mrk 421 is most closely aligned to the line-of-sight, its Doppler enhancement factor ($\delta = 7.7$) is greatest and its nonthermal radiation is most strongly beamed toward us. This explains why nonthermal emission is such a large fraction of the flux observed from Mrk 421 in the optical. The radiation from the jets is Mrk 180 ($\delta = 1.8$) and Mrk 501 ($\delta = 1.1$) are beamed less, and so galactic emission contributes a larger fraction of the optical flux. In addition, relative jet alignment explains why flux variability is more pronounced in Mrk 421 than it is in the other two sources.

References

Angel, J.R.P., and Stockman, H.S. 1980, Ann. Rev. Astr. Ap., 18, 321.

Blanford, R.D., and Königl, A. 1979, Ap.J., 232, 34.

Kellermann, K.E., and Pauliny-Toth, I.I.K. 1981, Ann. Rev. Astr. Ap., 19, 373.

Kojoian, G., Sramek, R.A., Dickson, D.F., Tovmassian, H., and Purton, C.R., 1976, Ap.J., 203, 323.

Königl, A. 1981, Ap.J., 244, 700.

Maza, J., Martin, P.G., and Angel, J.R.P. 1978, Ap.J., 224, 368.

Mufson, S.L., Hutter, D.J., Hackney, K.R., Hackney, R.L., Urry, C.M., Mushotzky, R.F., Kondo, Y., Wisniewski, W.Z., Aller, H.D., Aller, M.F., and Hodge, P.E. 1984a, Ap.J., in press.

_____. 1984b, in preparation.

Ulrich, M.H. 1978, in Pittsburgh Conference on BL Lac Objects, ed. A.M. Wolfe (Pittsburgh: University of Pittsburgh Press), p. 192.

Ulrich, M.H., Kinman, T.D., Lynds, C.R., Rieke, G.H., and Ekers, R.D. 1975, Ap.J., 198, 261.

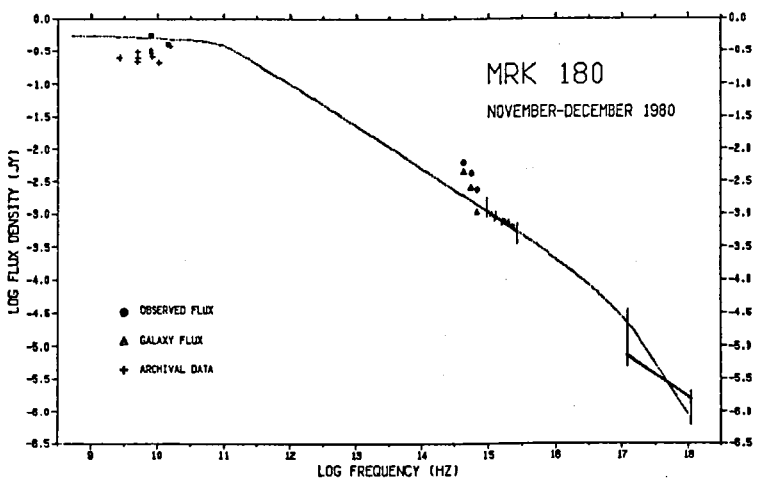

Fig. 1. Coordinated observations and best fit jet model (dashed lines) for Mrk 180.

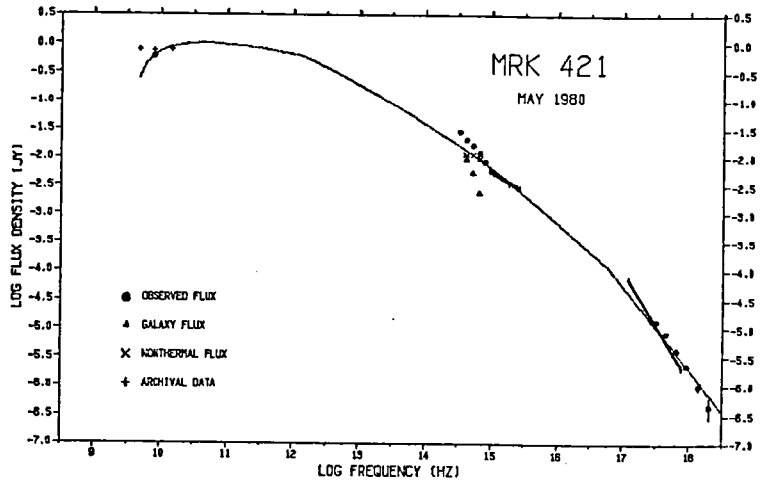

Fig. 2. Coordinated observations and best fit jet model for Mrk 421.

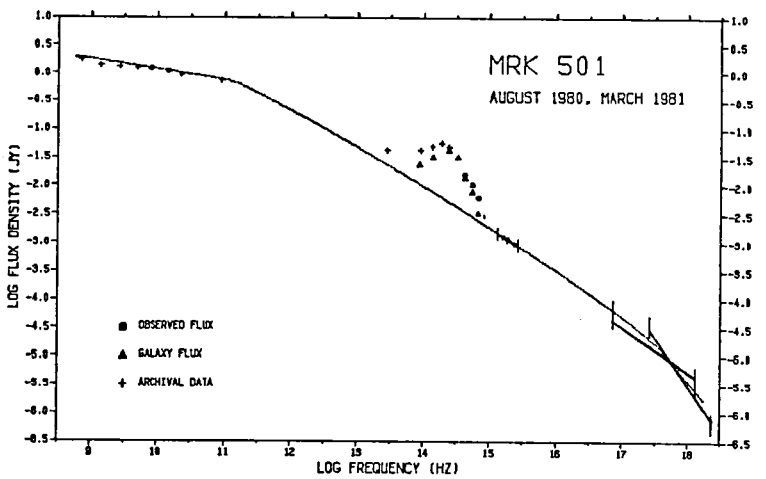

Fig. 3. Coordinated observations and best fit jet model for Mrk 501.